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Progress of thermoelectric power generation systems: Prospect for small to medium scale power generation

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ABSTRACT

This paper presents the progress of thermoelectric power generation systems and their potential to be incorporated in small to medium scale power generation systems with encouraging prospects of grid connection. To begin with this paper demonstrates the urgency and necessity of finding an alternative source of energy to replace the existing inclination of human race towards fossil fuels. Following this the potential of thermoelectric technology to be used with alternate energy sources is demonstrated. Development in the field of thermoelectric materials with high Seebeck coefficients, suitable for power generation modules is discussed in the literature review. New advanced materials and innovative techniques to utilise renewable energy for power generation using thermoelectric generators are described in the main body of this paper. Various active and passive cooling systems with thermoelectric power generation modules to enhance the performance of the system are illustrated in the paper. A brief literature survey is presented at the end about grid connection for thermoelectric generators .These advances in thermoelectric technology, places it in a comfortable position to become a major contributor to renewable and sustainable electricity production in the future, essentially replacing fossil fuels.

Contents

1. Introduction

Human need for energy has been on the rise since the industrial revolution in the 18th and 19th century. Mechanised manufacturing processes were evolved during this period and these were demanding high energy. Development in the field of technology further fuelled the demand for energy. During this period the need for energy was continuously increasing and it was realised that fossil fuel was not a permanent energy source. To support the technological development in the field of science and considering the rate at which the fossil fuels were exploited, many new technologies were evolved for alternate energy sources.

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In 1821 a German Physicist Thomas Johann Seebeck [1] observed that when two dissimilar metals were brought together and maintained at some temperature difference magnetic field is generated as evidenced by a deflection in the compass magnet. Initially he believed that it was due to the magnetism induced by temperature difference. However later he realised that it was the electrical current flowing through the dissimilar metals that introduced magnetic field. Primarily thermoelectric devices were more commonly used as heat pumps for cooling. Thermoelectric cell can be easily used in compact designs where cooling is necessary and efficiency of the system is not much of an issue. Till the middle of 20th century this technology was better known and the use of semiconductors with smaller band gap was found to perform better than just two metals [1]. This triggered the interest of researchers to explore the new materials that could have potential for thermoelectric power generation having a high Seebeck coefficient. In 1961, the National Aeronautics and Space Administration was the first organisation to implement thermoelectric technology in a real application where it was used to supply the electrical power to spacecraft [2]. Since then thermoelectric technology had found its way in the mainstream industry and has been used for various applications such as cooling and heating in trains [3,4], powering wrist watches[5], cool diode lasers [6] and many more.

During this period thermoelectric power generation was a new topic for research and it fascinated many researchers. The figure of merit of the known thermoelectric materials was quite low and hence the power generation efficiency could not compete with the then existing technology of internal and external combustion heat engines. Researchers tried many materials but were unsuccessful in exceeding the figure of merit beyond 1. This reduced the interest of research society towards thermoelectric and the future did not look bright for thermoelectric power generation to be one of the possible alternatives for fossil fuels. However during the 1990s there was an inflow of new ideas with evolution of some new materials to increase the figure of merit which once again reignited interest of researchers in the field of thermoelectrics and continued the quest for improving the figure of merit to the level where it can compete with the conventional heat engines [7–14].

Conventional bismuth chalcogenide such as Bi_2Te_3 and Bi_2Se_3 are amongst the best performing thermoelectric materials with figure of merit ranging in between 0.8 and 1.0 [15]. Lead telluride is another thermoelectric material which when doped with thallium achieves a figure of merit of 1.5 at 773 K [16]. Magnesium group compounds are good thermoelectric materials which have shown that their figure of merit is comparable with that of the bismuth chalcogenide. Figure of merit of 0.9 at 800 K for such materials has been reported by Rowe [15]. Recently skutterudite which is a cobalt arsenide mineral with variable amounts of nickel and iron has flashed the interest of the researchers for its thermoelectric properties. These materials have shown the potential for multistage thermoelectric devices which can exceed the figure of merit beyond 1 [15]. Another group of material called oxide thermoelectrics has a potential to be used at higher temperature as high as 1000 K. Example of an oxide thermoelectric material is combination of strontium titanate and strontium oxide. Figure of merit for the oxide materials is relatively lower than the conventional thermoelectric materials and was reported to be 0.34 at 1000 K by Wunderlich [17]. Half Heusler alloys have also shown a potential as high temperature thermoelectric materials especially as n-type materials. Figure of merit of 0.8 at 1000 K has been reported for MNiSn (M=Ti, Zr, and Hf) when doped with antimony [18]. Recently nanostructured materials have shown a great deal of promise in enhancing the figure of merit for thermoelectric materials beyond the limit where these devices can compete with the conventional heat engines and firm its position to produce electricity in mainstream power industry. Nanostructuring of bismuth chalcogenide has shown a significant improvement in figure of merit of the p-type material raising it up to 2.4 [19]. Quantum dots super lattice thermoelectric materials based on lead selenium and tellurium have shown an enhancement in the value of figure of merit to 1.5 which is more than the figure of merit for similar bulk material thermoelectric [20,21]. Recent research conducted in the AMES laboratory in conjunction with US EFRC programs suggests that adding small amount of rare earth metal to the thermoelectric material improves its figure of merit by distorting the local crystalline structure that enables high energy carriers to move through the material while providing the barrier to the lower energy carriers. It was shown by the researches at AMES laboratory that adding small amount of dysprosium to the thermoelectric material known as TAGS-85 increases its figure of merit from 1.3 to 1.5 [22]. Researchers at the University of Michigan along with US EFRC have also suggested that by creating a local atomic disorder in thermoelectric material would interrupt the atomic vibrations that control transport of heat and would result in low thermal conductivity[23,24].

2. Thermoelectric power generation systems

Development of new materials and extensive research on the nanostructured thermoelectrics have opened excellent avenues for thermoelectric devices to be used in the small scale to medium scale power generation applications using thermal energy. Rowe categorises thermoelectric power generators into isotopic thermoelectric generators and non-isotopic thermoelectric generators [25]. The reason for such classification of thermoelectric power generators is that the most prominent application of thermoelectric devices in stand-alone power generation system has been in the spacecraft using a heat source from a radioisotope. Use of radioisotope thermoelectric power generation system can only be justified for the spacecrafts since there is absence of oxygen in space to burn the hydrocarbons to run conventional heat engines [25]. Considerable research has been done on non-isotope thermoelectric systems for small to medium scale power generation from the renewable or sustainable energy heat sources. The next section of this paper presents the detailed review of the existing non-isotope thermoelectric power generation systems which have a potential of becoming the mainstream small to medium scale stand-alone or grid integrated power generation systems (Fig. 1).

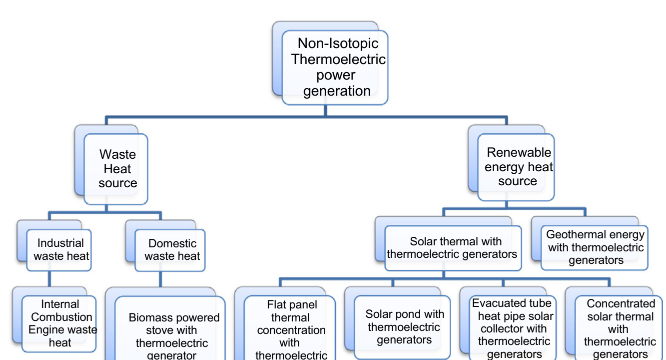

Fig. 1. Classification of non-isotopic heat sources and potential technologies related to these heat sources for small to medium scale power generation.

2.1. Power generation using high performance flat panel solar thermoelectric generators with high thermal concentration

This is the most recent work done on improving the performance of the thermoelectric generation systems using the solar thermal energy and thermal concentration. Kraemer has suggested the innovative technique to improve the efficiency of the thermoelectric devices using the conventional bulk materials under thermal concentration to improve the performance of the thermoelectric devices. Kraemer has illustrated in his research that traditionally photovoltaic systems were widely used as flat panel whereas solar thermal systems generally use the optical concentrators to achieve high temperatures source for power generation [26]. Using concentrated solar systems for producing electricity has been widely studied since long time. In 1964 Telkles has suggested an optical concentration system to achieve a high temperature difference across a ZnSb alloy p-type material and Bi alloy n-type material [27]. However due to the overheads involved in the tracking system for concentrated solar devices, Kraemer commented that such systems are unattractive due to their lower efficiencies [26]. Instead of the optical solar concentrating systems Kraemer recommended a different approach of thermal concentrating (Fig. 2).

Kraemer proposes a system that is fitted in a glass vacuum enclosure. The absorber plate with the selective absorber coating is placed on the top of the thermoelectric cell, while the selective absorber is facing the glass enclosure such that it is exposed to direct and diffused solar radiations. The thermoelectric elements used in this experiment are based on the nanostructured Bi_2Te_3 alloys [28,29]. The dimensions of the thermoelectric cells used for this research are 1.35 mm × 1.35 mm × 1.65 mm. Each of these elements is soldered to copper connector plates that are located at the bottom of the glass vacuum enclosure. These copper plates serve as the electrodes, heat spreader and the radiation shield. Heat spreader assists in cooling of the thermoelectric cell to maintain the temperature difference.

In Fig. 3(a) and (b) Kreamer shows the heat flow path of the solar energy incident on the selective absorber surface and the actual picture of the selective absorber surface used for the experiments while in Fig. 3(c) the definition of thermal concentration is illustrated. In his paper Kreamer states that using the systems suggested by Telkes [27] higher hot side temperatures could be achieved but the maximum temperature difference of only 70 °C and the highest efficiency of only 0.63% could also be achieved. Whereas Kreamer found that depending upon the thermoelectric material the optimal hot side temperature of 160–250 °C can be achieved using the solar absorber surface without any solar concentration. Kreamer suggested that the optical thermal efficiency working with the solar absorber surface is in the range of 70–80%. Kreamer claims that this high optical thermal efficiency will eventually lead to increasing the thermoelectric device efficiency to 5–6%, and can be further enhanced by having low solar concentration which does not attract any solar tracking system.

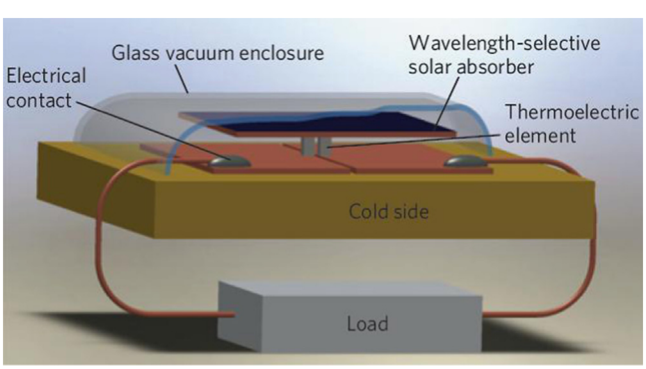

Fig. 2. Schematic of a solar thermoelectric generator cell enclosed in the glass vacuum enclosure with a flat panel covered with selective absorber as thermal concentrator, heat spreader and radiation shield [26].

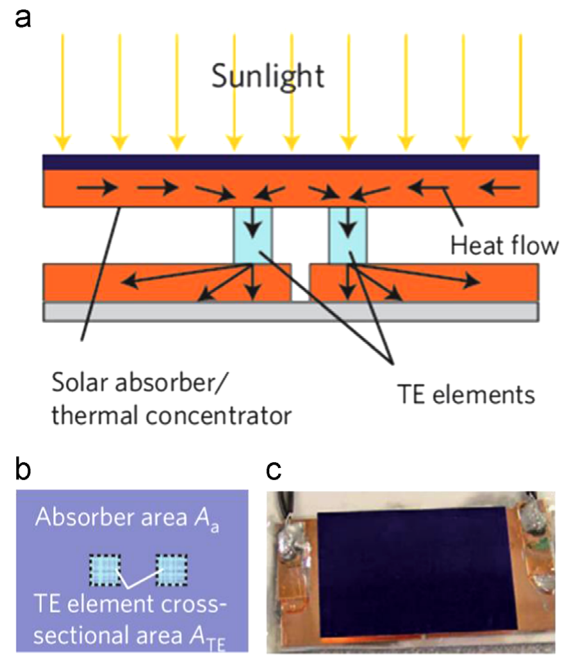

Fig. 3. (a) Schematic showing the heat flow through the selective absorber plate to thermoelectric cell and then to the cooling heat spreader plate [26]. (b) Schematic of the calculation for thermal concentration [26]. (c) Picture of the actual selective absorber surface used for testing by Kreamer [26].

Kreamer performed experiments on the set-up mentioned in Fig. 1 and recorded few readings to be compared with the simulation results. Kreamer has reported the peak efficiencies of 4.6% and 5.2% at solar radiation intensities of 1 kW/m^2 and 1.5 kW/m^2 for the thermoelectric cell used in this experiment. A comparative study is presented as well where Kreamer illustrates the solar thermoelectric efficiency for range of thermal concentration. His results suggest that the efficiency of the thermoelectric cell goes on increasing with the increase in the thermal concentration, however after a certain value of thermal concentration it will start to fall. This is due to the rise in temperature of the selective absorber surface which results in higher radiation losses. Kraemer has stated that there is a definite optimum thermal concentration for each thermoelectric cell material and different selective absorber surfaces.

Use of the vacuum enclosure to eliminate the convection losses from the absorber surface increases the efficiency of the thermoelectric cell. In one of the test performed by Kreamer he concludes that having a vacuum enclosure proves to be advantageous in case of interruptions in the solar radiation caused due to the sun being partially blocked by the clouds. The delayed thermal response due to the elimination of convection heat loss from the system results in continuous power output unlike in the case of the photovoltaic systems. The experimental data suggests that the thermal response time of 3 min can be achieved until the normalised open circuit voltage reduces by 50%. Using the heat spreader as the cooling medium that is fully passive helps to further reduce the losses that would be incurred in auxiliary power for active cooling system.

There has been some recent work on commercialisation of concentrated solar thermal power plants using mirror concentrators by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) based in Australia in conjunction with the industry partner Thermax limited based in India [30].

2.2. Power generation from solar ponds using thermoelectric modules and thermosyphon

An application of solar thermal storage system to generate electricity using the commercially available thermoelectric cell is proposed in this research by Singh [31]. In this research solar thermal energy stored in the salinity gradient solar ponds is proposed to be used for small to medium scale electricity generation using thermoelectric devices. These salinity gradient solar ponds can normally reach up to 80 °C in its lower convective zone (LCZ). Temperature difference between the lower convective zone (LCZ) and the upper convective zone (UCZ) in the range of 40–50 °C is proposed to be applied across the hot and cold side of the thermoelectric cell for power generation using a thermosyphon. A laboratory scale model is tested for validating the theory. Singh suggests that a solar thermal storage system coupled with the thermoelectric devices can be of great advantage due to its ability to supply base load power.

Salinity gradient solar ponds have been studied widely since long time and the researchers have proposed and developed various systems to utilise the thermal energy stored in the salinity gradient solar pond for power generation [32,33]. A 5 kW power plant using an organic Rankin engine was the largest power generation project using the solar pond near the Dead Sea in Israel [34]. Singh stated that large solar ponds have been successfully used for power generation although the smaller to medium size solar ponds have not been explored for their potential for producing electricity. He also claims that the few hundred square metres solar pond can store enough thermal energy that after converting to electricity can be enough for a single sustainable and energy-efficient house (approx. 2–5 kW-h/day electricity consumption) [31]. Singh also stresses on the reason to use the thermoelectric devices with solar ponds due to their reliable and silent operation of thermoelectric cells over the conventional heat engines. The importance of the high costs of the conventional heat engines even for a smaller electricity rating is stressed by him and compared it with the cost of the commercially available thermoelectric cells instead.

Singh's proposed design uses the passive cooling system for maintaining the cold side of the thermoelectric cells at lower temperature. The passive cooling system involves the use of thermosyphon and the relatively colder water in the UCZ of the solar pond. Thermosyphon has been widely researched for many decades and is very efficient in transferring heat in its present technological state and manufacturing of different sizes of thermosyphon is easily possible [35–37].

The power generation proposed by Singh is shown in Fig. 4(a). This system uses the heat from LCZ of the solar pond for the hot side of the thermoelectric cell and the relatively cooler water from the UCZ of solar pond for cold side of thermoelectric cell to obtain the temperature difference. In this proposed design heat is transferred from the bottom of the solar pond to the top of the pond using the thermosyphon. Thermosyphon is an evacuated copper tube charged with distilled water and held upright such that the gravity can be used for transport of the condensed liquid water back to the evaporator at the bottom. Singh has presented the temperature and salinity gradient data for a small scale experimental solar pond situated in the RMIT University, Australia. This pond is 8 m in diameter and 2 m deep and is charged with sodium chloride saline water with varying salinity from top till the bottom of the pond. Maximum temperature of 60 °C at the bottom of the pond with the density of 1200 kg/m^3 is reported by Singh [31].

Fig. 5(a) represents the schematic of the laboratory test set-up for simulating the outdoor conditions similar to the solar pond. This set-up consists of the hot water bath heated using the resistive electric heating elements that simulate the LCZ of the solar pond while the UCZ is simulated by circulating the cold water in the chamber situated at the top of the system. It is proposed by Singh to attach the thermoelectric generators at the top of the octagonal copper tube thermosyphon [31]. Two rows of thermoelectric cells with hot side facing inwards are attached to the octagonal copper tube while the cold side is directly exposed to the cold water chamber. In all 16 commercially available thermoelectric generators were used in this experiment for demonstration of the proposed system. Fig. 5(b) illustrates the actual test set-up while in its operation mode.

According to the results in Singh's literature, experiments were performed for LCZ temperature ranging from 50 to 90 °C. Maximum power output was 3.2 W from 16 thermoelectric cells connected in series at the temperature difference of 27 °C. The open circuit voltage of 26 V and short circuit current of 0.4 A were observed during these experiments. Finally Singh claims that the proposed system with fully passive devices such as solar pond, thermosyphon and thermoelectric generators is capable of producing power for the remote area power applications. He also suggests that it is possible to extract the heat and convert it to electricity from small to medium size solar ponds by using the shelf thermosyphon and thermoelectric generators.

2.3. Power generation using evacuated tube heat pipe solar collectors and thermoelectric modules

The work presented by He proposes the power generation and water heating system incorporating the thermoelectric generators with evacuated tube solar collectors as a heat source and the active

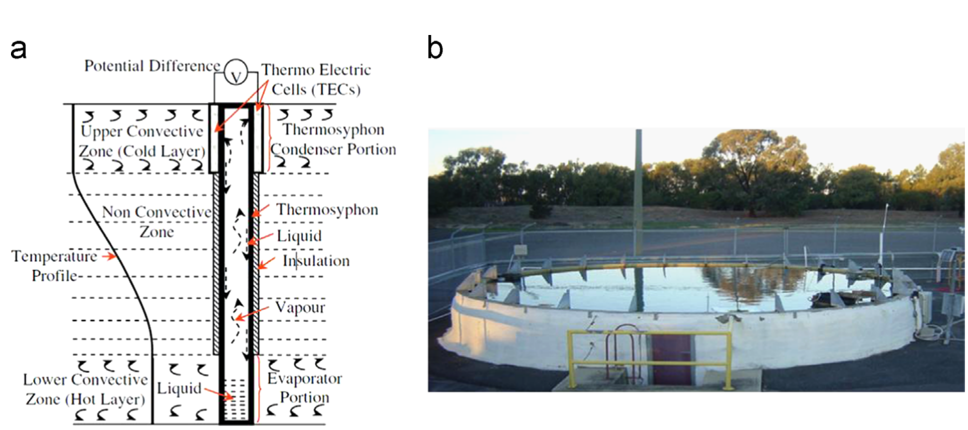

Fig. 4. (a) Schematic of the proposed system for power generation using solar pond and thermosyphon with thermoelectric generators [31]. (b) Salinity gradient solar pond located at the RMIT University in Australia [31].

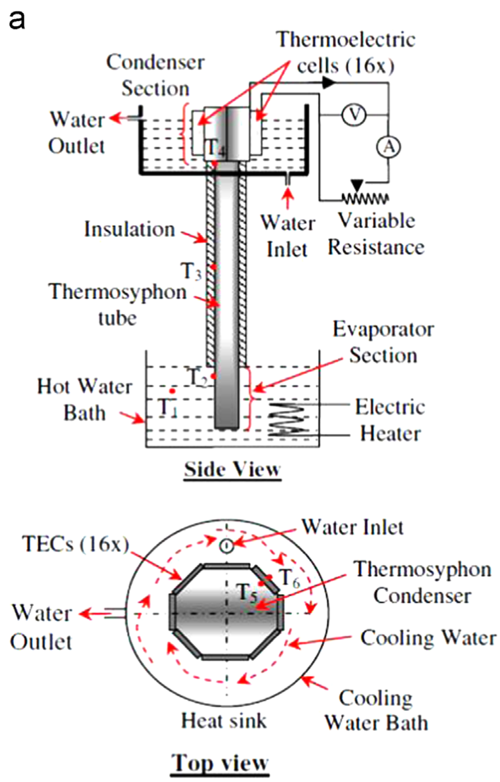

Fig. 5. (a) Schematic of the test set-up with hot water bath representing the LCZ, thermosyphon, thermoelectric cells and cooling water representing the UCZ [31]. (b) Actual experimental test set-up [31].

cooling using the cold water jacket. An integrated evacuated tube heat pipe and a thermoelectric generator are proposed for water heating and power generation [38,39]. The author illustrates the high potential of the evacuated solar water collectors and mentions the advancement in its technology. He also states that the large scale installations of evacuated solar water collectors have been done across the world with average annual growth rate of 30% for its market [40]. One of the global surveys suggests that almost 106 million m^2 of evacuated tube solar water collectors have been installed worldwide with the lifetime expectancy of greater than 15 years [41].

In this research initially the author refers to the past literature to provide some comparison between the flat plate solar collectors and evacuated tube solar collectors giving the average temperatures and efficiencies of both the systems and explaining the superiority of evacuated tubes over the flat plate [42]. Due to all the positive indications about the temperature and efficiency of evacuated tube water collector, the author suggests incorporation of this solar thermal energy collector system with the thermoelectric generators. Although He [38] acknowledges the current progress in the technology of thermoelectric devices and low efficiencies of existing commercially available thermoelectric cells, he believes that the compactness and reliability of thermoelectric generators can overcome this drawback [38]. He also mentions the increasing number of manufacturers making the thermoelectric generator modules which has dropped its cost in the market significantly.

Thermoelectric generators have a typical thermal conductivity of 1.5 W/m-K with the thickness of 4 mm. So for temperature difference of 60–100 K heat flux exceeding 20 kW/m^2 will be required. He also attracts attention towards the fact that the normal average solar radiation on the horizontal surface being approximately 1 kW/m^2 which is quite low for better working of thermoelectric generators without any solar concentration

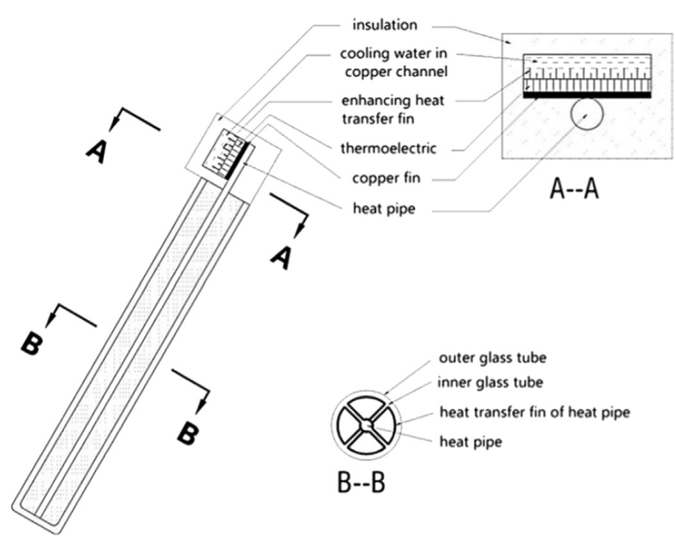

Fig. 6. Schematic of integrated heat pipe type evacuated tube solar collector with direct incorporation of thermoelectric generator [38,39].

systems. He also acknowledges the proposals by other researchers of using the concentrated solar systems for thermoelectric power generation but debates the justification of the costs incurred in installation and maintenance of solar tracking devices [43]. To combat this problem he proposes a system with direct incorporation of thermoelectric generator with heat pipe type evacuated tube water collector which helps in converting the low heat flux to higher heat flux by having the larger evaporator area and smaller condenser area [38] (Fig. 6).

He has presented a detailed mathematical model for prediction of the temperature of water in the evacuated tube water collector, its thermal efficiency and thermal and electrical performances of

the thermoelectric generator under test. The theoretical model and its results were validated by the results of the experimental set-up (Fig. 7).

For the experimental testing of the proposed system, the commercially available thermoelectric generator of 40 mm length × 40 mm width × 4 mm thickness is used. According to the results presented in the paper thermoelectric generator reaches the maximum power value of 0.98 W per thermoelectric generator at the solar radiation of 850 W/m^2 and cooling water temperature of 30 °C. Another test performed by the author with solar radiation of 780 W/m^2 is reported in the literature where the temperature of cooling water reaches 40 °C and the power output is 0.78 W per thermoelectric generator cell.

He [39] has also studied the parametric analysis of thermal and electrical efficiencies of the evacuated tube solar heat pipe system incorporated with the thermoelectric generators. He has described the effect of water temperature, solar irradiation, number of thermoelectric elements and thermal conductivity of insulation on the thermal and electrical performance of the system. It is clear from the analytical results that the thermal and electrical efficiency of the system decreases with the increase in cooling water temperature. He has presented the trend in decrease in thermal and electrical efficiency for solar radiation of 1000 W/m^2 when cooling water temperature increases from 25 °C till 55 °C [38,39]. He claims the reduction of 20–25% of conversion of thermal energy to electrical energy due to 30 °C increase in cooling water. Further the author has demonstrated the simulation results for the effect of change in solar irradiation on the thermal and electrical efficiencies at cooling water temperature of 45 °C [38,39]. According to the simulation results the electrical efficiency increases with increase in solar irradiation due to continuous increase in the surface temperature of the heat pipe. Thermal efficiency responds differently than electrical efficiency to change in solar radiation. The temperature of heat pipe increases with increase in solar radiation that causes the radiative heat losses to increase. It is observed from the simulation that maximum thermal efficiency of 56.56% can be achieved at 500 W/m^2 [38,39]. The number of thermoelectric elements affects the electrical efficiency of the system. It is seen from the analytical results in the literature that optimum thermoelectric elements for solar radiation of 400 W/m^2 is 50 and increases to 80 for solar radiation of 1000 W/m^2. He briefly mentioned

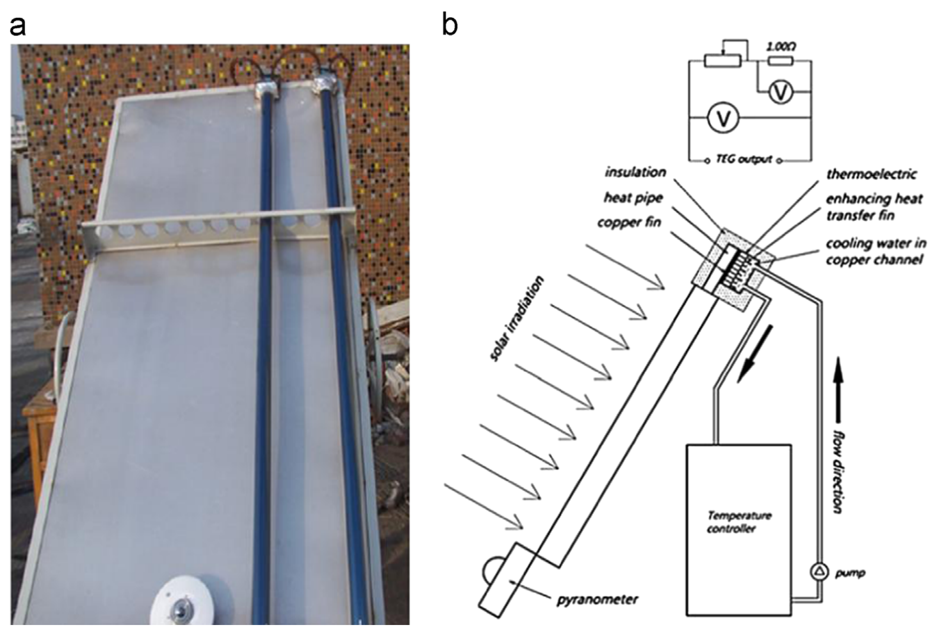

Fig. 7. (a) Actual photograph of the heat pipe type evacuated solar water collector with thermoelectric generators. (b) Schematic of the proposed experimental system [38].

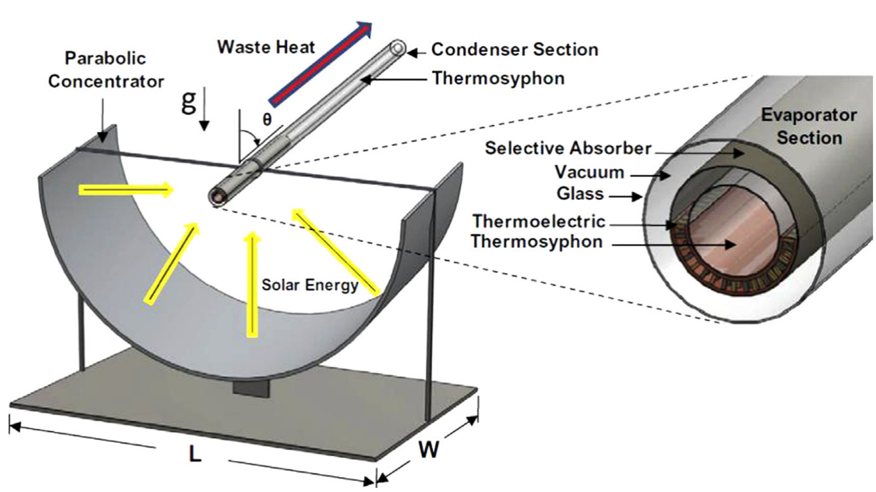

Fig. 8. Schematic of concentrated solar thermoelectric system with thermoelectric generator attached around thermosyphon for carrying the heat to condenser to be used for some secondary application [45].

that the better thermal insulation leads to improved electrical efficiency. Finally The author states that incorporation of the combined thermoelectric module with glass evacuated heat pipe solar collectors is a feasible option for household supply of hot water as well as electricity generation. He also compares the electrical efficiency of this system with the organic Rankine cycle system running on heat from evacuated heat pipe solar collectors. Although the electrical efficiency of the Rankine cycle engine is higher (3–4% [44]) as compared to solar heat pipe thermoelectric system with electrical efficiency (1–2%), the author recommends to have a solar heat pipe thermoelectric system due to its simplicity of operation, reliability of working and the lower investment cost for installation and regular maintenance.

2.4. Power generation using the concentrated solar thermal system incorporating thermoelectric generators

This literature presents the hybrid concentrated solar thermoelectric system using thermosyphon for passive heat transfer for various secondary thermal applications that require relatively medium to high temperature and high quality heat such as chemical drying or aluminium smelting. A parabolic trough mirror is used for solar concentration with the thermoelectric generator installed at the target area with selective surface coating for power generation. Thermoelectric generators are mounted around the thermosyphon that carries the remaining thermal energy to the condenser. Bismuth telluride, lead telluride and silicon germanium thermoelectrics are considered in this research for power generation. This hybrid solar thermoelectric system is investigated for temperature ranging from 300 to 1200 K and solar concentration of 1–100 sun [45].

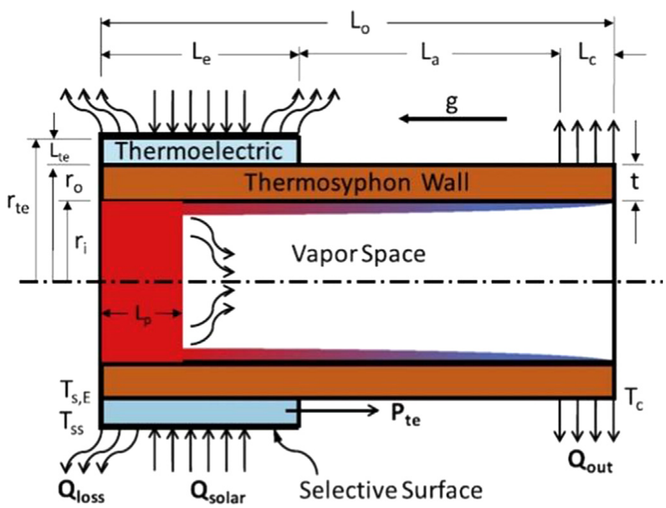

Fig. 9. Schematic cross section of the thermoelectric generator attached to the two phase thermosyphon showing the heat flow path through the system [45].

In this research Miljkovic illustrates the advantage of using the thermoelectric generator directly with the concentrated solar thermal source instead of concentrated or non-concentrated hybrid solar photovoltaic thermoelectric systems as suggested by few researchers [45–50]. In his paper Miljkovic states that while using the hybrid photovoltaic thermoelectric systems the thermoelectric generators have their operation limited at low temperature due to significant degradation of electrical efficiency in photovoltaic at elevated temperatures (Fig. 8).

A parabolic trough concentrator is used in this design to achieve the required solar concentration. An evacuated tube containing thermosyphon with thermoelectric generator around the outer surface is mounted at the target of the parabolic trough concentrator. Evacuated tube helps to prevent thermal losses at the target due to convection and helps in increasing the hot side temperature of the thermoelectric generators. A two phase thermosyphon is inclined along length to facilitate the angle for gravity return of the working fluid from condenser back to the evaporator [45] (Fig. 9).

A theoretical model based on thermal resistance of each component in the system is presented by Miljkovic in his literature. Three combinations of thermoelectric material and thermosyphon working fluid are studied and presented in Miljkovic's paper. Water copper thermosyphon is used with bismuth telluride thermoelectric material for lower temperature range of 300–550 K, mercury–stainless steel thermosyphon with lead telluride for medium temperature range of 525–850 K and potassium–nickel thermosyphon with silicon germanium thermoelectric material for higher temperature range of 850–1200 K [45]. Miljkovic claims that the overall system efficiency increases with increase in the solar concentration though it is largely affected by the condenser temperature. Condenser temperature determines

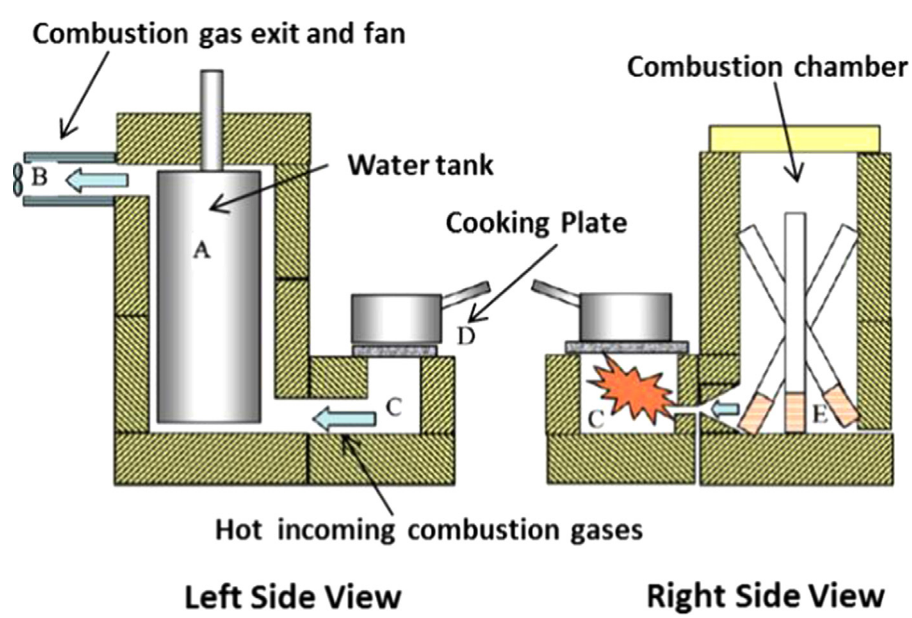

Fig. 10. Schematic side views of biomass fired stove with combustion chamber, burner and water heating chamber for thermoelectric power generation [51].

the temperature difference between the hot and cold side of the thermoelectric generator. Optimum working efficiencies with respective temperatures established by Miljkovic are 34.4% at condenser temperature of 500 K and solar concentration of 50 sun for the bismuth telluride thermoelectric generator and water copper thermosyphon is 48.1% at 776 K and solar concentration of 100 sun for the lead telluride thermoelectric generator and mercury stainless steel thermosyphon. In conclusion Miljkovic states that the proposed system has an advantage over the hybrid photovoltaic thermoelectric system due to its ability to operate at higher temperature using various combinations of thermoelectric materials and thermosyphon material and working fluids. Such systems can be very efficient for medium scale power generation in a small scale industry combined with its thermal application ability.

2.5. Power generation from thermoelectric devices using the biomass powered stoves

Lastly an innovative proposition by Champier of thermoelectric power generation from biomass cooking stoves is discussed in this paper [51]. The system proposed by Champier is mainly focused to address remote area power supply to support the electrical needs of the energy efficient house. Use of biomass stoves is extensive in the developing countries and mainly in their rural areas. Champier has designed a novel thermoelectric power generation system from the heat used for cooking in the household kitchen and then proposed the design where an thermoelectric power generation system can be incorporated in already existing biomass cooking stoves [51]. Traditional open fire biomass stoves have a low thermal efficiency due to incomplete burning of the fuel, and much of the heat produced is wasted through the exhaust of these traditional biomass stoves [52,53]. Champier acknowledges the several previous attempts to incorporate thermoelectric power generation systems with the waste heat of cooking or water heating from wood stoves [54–56].

Champier has performed some basic performance tests on the commercially available thermoelectric generators with a test set-up simulating the conditions similar to the biomass stove [51]. Champier also compares the performance of the tested thermoelectric generator modules with the predicted performance to confirm the simulation model presented in the paper (Fig. 10).

Champier had come up with an improved design of the biomass fired stove to accommodate the thermoelectric generators under the heating plate used for cooking or under the water tank where the waste heat from the stove is used for heating the water for household use [51]. According to Champier's investigation if the thermoelectric cells are attached under the water heating tank, the available flux per cell is too low to have a good efficiency of the thermoelectric generators. In his second suggestion Champier mentions to have a bigger cooking plate with a secondary water tank connected to the main water tank for cooling of thermoelectric generators.

Champier has conducted some experiments by simulating the conditions in his new design of the biomass fired stove. In his test set-up, he uses a gas burner to simulate the heat source and water tank as the cooling source for thermoelectric generators. Experimental results have shown that at the temperature difference of 160 °C maximum power output from four thermoelectric generators is 7 W. He also mentions about the use of battery to store the energy and the electrical system needed to support the use of the household appliances with the generated power and estimated the regulated power output of 6 W from 4 thermoelectric cells. He has also presented the cost analysis of the system and future price predictions of the key components like thermoelectric modules.

This work presents the new biomass fired stove design for rural regions in developing countries using the commercially available thermoelectric generators for power production in remote location away from grid.

2.6. Thermoelectric power generation using waste heat from internal combustion engine exhaust

Significant research has been done on examining how to utilise the energy from the internal combustion engine exhaust for power generation using thermoelectric generators [57,58]. Crane [59] has done some studies on optimisation of heat exchangers for heat recovery from the automobile exhaust using the thermoelectric generators. His study included an energy balance of components of the automobile system by accounting for auxiliary power loss due to the fan and fluid pump for the cooling system with thermoelectric power generation. Karri [60] has presented the detailed case study of performance of the thermoelectric power generation systems using the waste heat from two automobile systems – engine of a sports utility vehicle and the stationary natural gas generator. He has presented the simulation models with thermal and electrical performance of thermoelectric generators used with sports utility vehicle and stationary natural gas engine. Fig. 11 shows the schematic of the two engines coupled with the thermoelectric generators for power generation.

Karri [60] has examined the impact of thermoelectric generators on the sports utility vehicle at various speeds and stationary compressed natural gas engine at various electrical loads. He has also presented the modelling approach for simulation of both the case studies and determined the optimum coolant flow rate and thermoelectric leg aspect ratio for sports utility vehicle and optimisation of number of thermoelectric modules and their arrangement for maximum power output at various configurations of parallel and series combinations.

The benefits of using the thermoelectric generators with internal combustion engines are presented in Karri's paper. Karri [60] claims that sports utility vehicle can generate 100–450 W that will result in 2–2.3% fuel saving. However for compressed natural gas stationary engine the fuel saving increased to almost 3% primarily due to the absence of rolling resistance and parasitic losses. This was also due to the absence of space constraint that allows the increase in the size of thermoelectric generator module on the stationary compressed natural gas engine.

Extensive industry involvement in practical commercialisation of thermoelectric power generation is demonstrated by Kajikawa in his literature [61]. Japanese company Komatsu Ltd. has installed a 1 kW thermoelectric power generation system using exhaust gases from the 500 kW diesel generator [62].

2.7. Waste heat recovery applications

There have been numerous attempts by researchers to utilise low grade waste heat from various sources and convert it to high grade electricity using thermoelectric generator systems. In one of the similar approach Toshiba corporation demonstrated the heat recovery from the surface of the mock up electric transformer. With 36 thermoelectric generator modules and 6 fin plate type heat exchangers the heat recovery unit was able to generate 55 W electrical power with system efficiency of 1.8% at temperature difference of 80 °C. Another recent improvement in application of waste heat recovery includes the use of ring structured thermoelectric modules. Instead of conventional plate type modules Gao [63] has suggested the tube shaped thermoelectric generators to be used in conjunction with the working fluids in heat exchangers flowing through pipes.

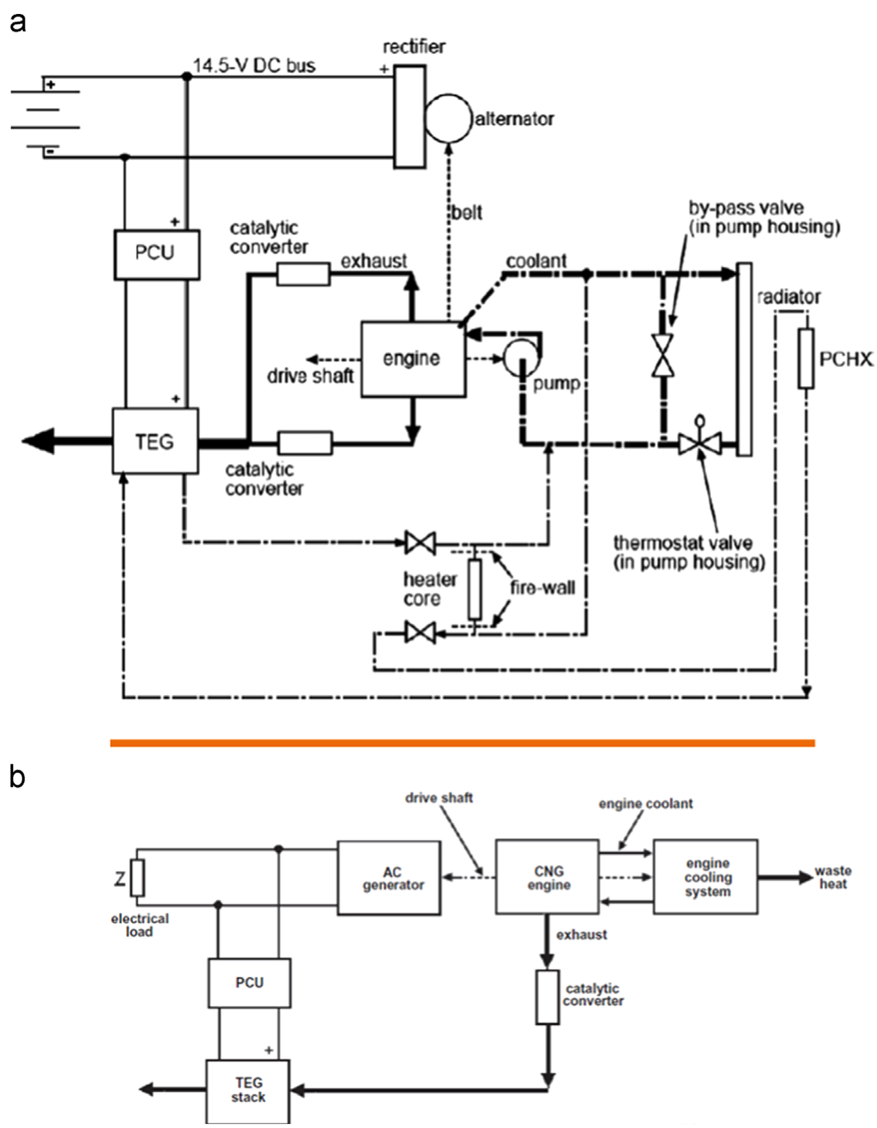

Fig. 11. (a) Schematic of sports utility vehicle engine coupled with the thermoelectric generator. (b) Schematic of the stationary compressed natural gas engine with thermoelectric generator stack for power generation.

3. Grid integration of thermoelectric power generators

Thermoelectric power generators produce a direct current with voltage directly dependent upon the temperature difference between the hot and cold side of thermoelectric generator. Like most of the renewable energy power generation sources thermoelectric generation systems needs signal conditioning and power regulation before they can be connected to the main grid. Extensive research has been done on the power electronics for grid connection of photovoltaic and wind power systems [64] and it is in real use at many solar photovoltaic and wind power plants. There is a need of special power electronic and power regulation system since the operating conditions for thermoelectric generators are different than that for the solar photovoltaic and wind power systems. Molina has presented an innovative power conditioning system specially for grid integration of thermoelectric generators [65]. Molina proposes a control strategy for converting the power from DC voltage to AC voltage and to keep the thermoelectric array working at the maximum power point at all the time. A novel power condition system for grid integration of thermoelectric power generators to control the active and reactive power is presented by Molina.

4. Future of commercial thermoelectric power generation

The technological development in the field of thermoelectric materials, different approaches to applications and identification of various sources of heat are leading to compound benefit for this technology to commercialise in diverse industries. All recent publications in the field of thermoelectric materials suggest that the endeavour to reach the figure of merit in the range of 1.5–2 is not beyond reach. With a figure of merit of thermoelectric material of 2, it can comfortably replace the existing complex power generation heat engine systems which are mostly consuming non-renewable fossil fuel. These materials can also make it possible for thermoelectrics to be used in space heating and cooling applications that will replace the existing complex heat pumps. These developments in better ZT materials will also enable us to practically utilise more waste heat from different waste heat sources. The research community is making itself equipped for a higher ZT material to evolve with exploring various applications that can efficiently utilise the heat to convert to electricity with one of the most prominent heat source being considered as solar thermal energy. Cogeneration in vehicles is also considered to be one of the practical ways of implementing thermoelectric technology.

5. Conclusion

This paper presents the collection of existing thermoelectric power generation technologies that have shown great potential in contributing towards future small to medium scale power generation systems. This review of the literature shows the use of advance material in thermoelectric generator, use of advanced technology for heat source and some innovative techniques for cooling of thermoelectric generator for enhancing their thermal and electrical performance. Most of the above mentioned techniques show a good potential to become the mainstream small and medium scale power generators as a remote stand-alone systems or a grid integrated power plant. Innovative systems like high performance solar flat panel thermoelectric generators with thermal concentration system, solar pond integrated thermoelectric power generation system and concentrated solar thermal system with thermoelectric power generators have a great potential to be utilised for medium scale power generation. On the other hand systems like biomass stove and evacuated tube heat pipe solar collector with thermoelectric system can be good for small scale power production for individual household use. Heat recovery systems used in internal combustion engine show an attractive option of improving the efficiency of the automobile and increase the fuel saving in case of the stationary application as power generators. All these new systems are supported by the latest research on thermoelectric materials to improve their figure of merit such that this technology can overcome the barrier of being less efficient than conventional heat engines. With further advances in materials and system design for thermoelectric generators the future of these systems look bright for both mainstream and small scale power generation.

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